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13. ABSTRACT (Maximum 200 words)

The objective of this effort was to develop the techniques for fabricating a multifunctional lightweight structure that could be used as armor for mobile vehicles such as personnel carriers. These fabrication techniques are scalable to manufacturing production levels. For this program, square cell LCA honeycomb with both maraging steel and super invar compositions were fabricated using SAI's patented technology to have cross sections of one inch square. These honeycombs have 5 cells/side or 25 cells/in2 and all walls have the same thickness. For these extrusions, cell size was held constant and varying the wall thickness from 0.10 to 0.20 inches varied the relative density from 10 to 20%. Bulk densities were ~1, 1.3, and 1.6 g/cc. Samples were supplied to Robert Frey and John Runyeon, ARL, Aberdeen,for evaluation by high strain rate experimental techniques to test the effect of macrostructure density on energy absorption to optimize the topology of these systems for maximum structural response for specific boundary and loading conditions. In this delivery were a total of 67 samples with a length of five inches and 46 samples with a length of one inch, all of which are pictured in the results section.

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Lightweight Multifunctional Linear Cellular Alloy Ballistic Structures

from

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Lightweight Multifunctional Linear Cellular Alloy Ballistic Structures

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Executive Summary

The objective of this effort was to develop the techniques for fabricating a multifunctional lightweight structure that could be used as shock mitigators or armor for mobile vehicles such as personnel carriers. These fabrication techniques are scalable to manufacturing production levels. These cellular structures are a heterogeneous combination of a high strength impervious macrostructure, a designable void component, and possibly, an additive energy-absorbing feature to place in the void component. These are in essence hybrid macrostructures that are a combination of high strength and lightweight engineered composites with heterogeneity at millimeter scales in the form of a superstructure and at the micrometer scale due to the wall microstructure that is finer than melt processed alloys due to solid state sintering for densification.

For this program, square cell LCA honeycomb with both maraging steel and super invar compositions were fabricated using SAI's patented technology to have cross sections of one inch square. These honeycombs have 5 cells/side or 25 cells/in^2 and all walls have the same thickness. For these extrusions, the cell size was held constant and the relative density was varied from 10 to 20% by varying the wall thickness from 0.10 to 0.20 inches. Prior to the program, the lowest density that had been fabricated in these structures was 25% relative density (RD). For this program, structures were made at ~10, ~15, and ~20% RD. Both steels have a density of 8.2 g/cc. The bulk densities for the honeycomb fabricated here were ~1, 1.3, and 1.6 g/cc. The invar honeycomb shown in Figure 1 has a cell size of 0.19 inches, a wall thickness of 0.019 inches and a relative density of 20%.

Samples have been be supplied to Robert Frey and John Runyeon, Army Research Laboratory, Aberdeen Proving Ground, MD for evaluation by high strain rate experimental techniques to test the effect of macrostructure density on energy absorption to optimize the topology of these systems for maximum structural response for specific boundary and loading conditions. In this delivery were a total of 67 samples with a length of five inches and 46 samples with a length of one inch, all of which are pictured in the results section.

In addition, a simulation titled "Numerical Analysis of Ballistic Impacts onto Linear Cellular Alloys" was modeled by Mr. Ry Doolittle in the School of Materials Science and Engineering at Georgia Tech under the direction of Professors Naresh Thadhani and Joe Cochran. These calculations simulated the effects of 0.5-inch diameter right circular cylinders impacted into the LCAs fabricated in the program. The model analyzed the effects of both aluminum and steel projectiles with a velocity of 400, 600, and 1000 m/s when impacted axially at the center of the one-inch square LCAs. The results suggested that stopping all the projectiles was possible. This program did not fund this simulation but it has been submitted along with this final report in support of the overall effort.

Figure 1. Super Invar, square cell LCA with a cell size of 0.19 inches and a relative density of 20%.

Background

Linear Cellular Alloys (LCAs) are low-density metal honeycomb structures fabricated using a novel powder extrusion technology developed by the low density structures group at Georgia Tech[1] . The LCA structures can be fabricated via commercial extrusion processes into many topologies and relative densities. Examples of cross-sections of various LCA designs, fabricated at Georgia Tech, are shown in Figure 2. The LCA structures provide high levels of energy absorption; 5 to 7 times that of that of conventional materials. Maraging steel honeycomb structure having a density of 2.1 g/cm^3 and yield strength ~650 MPa, has been shown to absorb ~180 MJ/m^3. Figure 2 shows stress train curves for maraging steel under quasistatic and dynamic loading.[2] The specific energy absorption is found to increase as the strain rate increases going from quasistatic to dynamic loading. The energy absorption as well as deformation and/or buckling mechanisms during collapse of the LCAs are also being modeled using finite element simulations. Quasi-static compression test behavior of a high stiffness radial prismatic structure fabricated from Maraging 200 alloy is shown in Figure 4 for the structure unfilled and also filled with epoxy. Without filling, the structure has strength of ~ 490 MPa and epoxy filled, a strength of ~ 560 MPa is demonstrated. The unfilled structure demonstrates energy absorption of ~ 180 MJ/m^3.

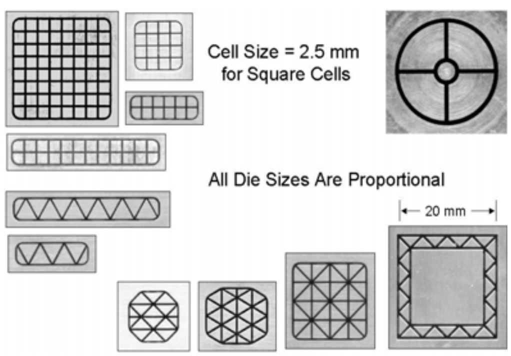

Fig. 2. Examples of cross -sections of other designs of LCAs fabricated at Georgia Tech for various applicatior

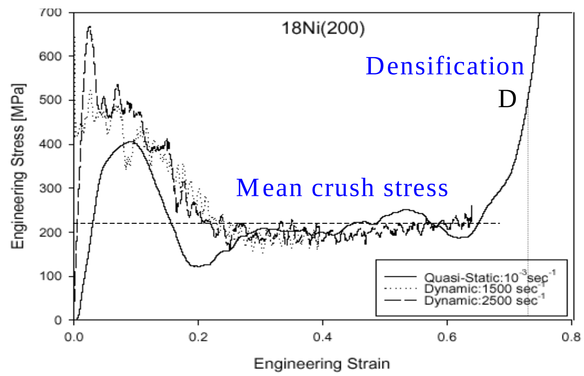

Fig. 3. Comparison of crushing behavior of square cell 18Ni(200) Maraging Steel LCAs under quasistatic and dynamic (split Hopkinson bar) loading (Hayes, 2001).

The dynamic impact response of filled (with epoxy) and unfilled linear cellular alloys has been studied using reverse Taylor-rod impact tests at impact velocities of ~125 and ~400 m/s, using the Georgia Tech 80-mm diameter gas gun[3]. The results illustrated that at the lower impact velocities, the LCAs have dynamic yield strengths of 669 MPa in unfilled and 734 MPa in epoxy-filled condition and they undergo minor deformation with slight increase in diameter of impact surface. At higher impact velocities and strain rates exceeding 6 x 10^3 m/s, the dynamic yield strength is raised to 3.3 GPa in unfilled and 3.8 GPa in epoxy-filled condition, Figure 5. The corresponding energy dissipated in the process of plastic deformation estimated to be about 500 MJ/m^3 at ~400 m/s impact velocities, Figure 6. These levels of energy dissipation during axial compressive loading are quite significant and can be employed to provide high levels of blast and ballistic protection.

[1] Joe Cochran, Jim Lee, Tom Sanders, US Patent 6,582,651 B1, "Methods of Producing Metallic Articles by Direct Chemical Conversion of Nonmetallic Articles", June 24, 2003.

[2] Hayes, A., *Compression Behavior of Linear Cellular Steel*, M.S. Thesis, School of Materials Science and Engineering, Georgia Institute of Technology, Atlanta, GA, 2001.

[3] Justin Clark, "Dynamic and Quasi-Static Mechanical Properties of Fe-Ni Honeycomb", PhD Dissertation, Materials Science and Engineering, Georgia Tech, May (2004)

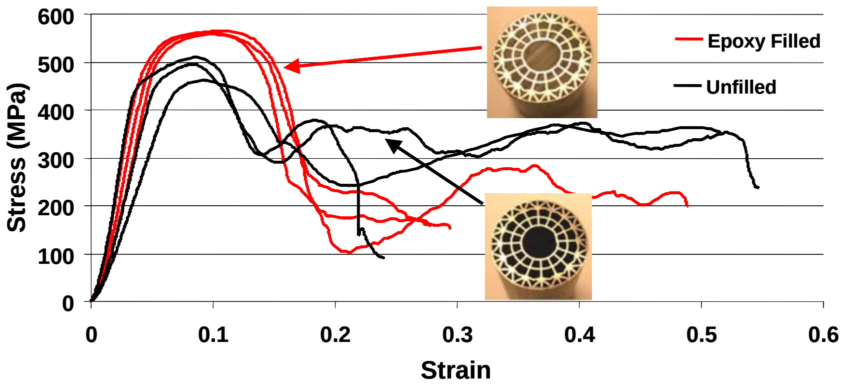

Figure 4. Quasi-static compression behavior of a high stiffness radial prismatic structure fabricated from Maraging 200 alloy for the structure unfilled and also filled with epoxy.

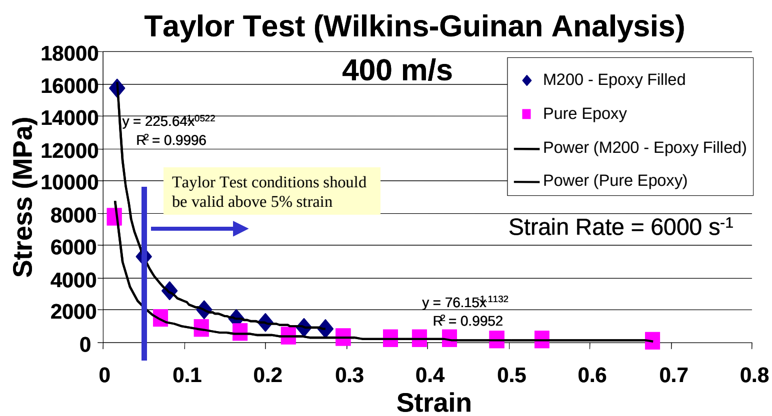

Figure 5. Stress-strain dynamic behavior of a high stiffness radial prismatic structure (Figure 4) from the Taylor test using a Wilkins-Guinan analysis showing stress increase compared to quasistatic values.

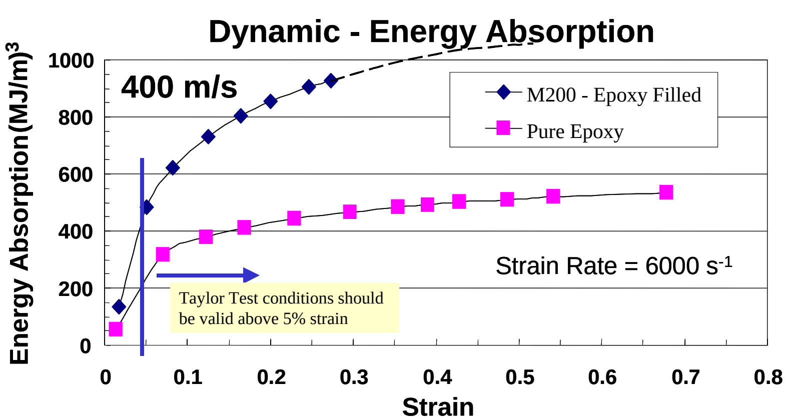

Figure 6. Dynamic energy absorption at stain rate of 6000 s^{-1} for high stiffness radial prismatic structure which provides an estimate of ~ 500 MJ/m^3 for epoxy filled Maraging 200 LCA

LCA Fabrication Procedures

Manufacturing Scale-Up of LCA - In the LCA process, honeycomb is fabricated by extruding mixed metal oxide paste that is converted to dense wall alloy honeycomb by direct reduction in hydrogen and solid state sintering to near theoretical wall density. In this program, larger size honeycomb (1.31" square) was extruded and reduction/sintering were at Georgia Tech in a 16 ft^3 hydrogen furnace. For extrusion, three new dies were fabricated for a cost of $8,500, as described below. These dies were designed to extrude square cell honeycomb at relative densities of 10, 15 and 20 % with the dimensions shown in Table 1. The alloy compositions were high strength maraging steel (M200) and Super Invar.

Extrusion Dimensions and Dies -The square cell honeycomb was extruded with the dimensions shown in Table 1. These dimensions were selected for several reasons. First, the total extruded width, ~1.32 in. was limited because extrusion was in a 2 inch diameter piston extruded and the honeycomb diameter was ~1.85 in. which is the largest square honeycomb possible with this extruder. Second, the cell size was selected be as large as possible to provide relatively thick walls to minimize defects but the number of cells needed to be sufficiently large to provide mechanical properties representative of larger arrays[2]. Square cell arrays of 5x5 have been shown to provide compressive behavior similar to larger arrays. The sintered dimensions are controlled by proper paste preparation and composition of raw materials. Shrinkage from reduction and sintering is typically 25% and this value was used to project sintered dimensions.

A digital image of the die designed for these extrusions is shown in Figure 7. The die land is shown in Figure 7a as an array of square posts with the proper separation to from the desired wall thickness. The entrance to the die is seen in Figure 7b where a series of feedholes is used to supply paste to the die land. Obviously, three separate dies are needed to provide different relative density. Not show is a square collar that fits around the die land to from the exterior wall of the extrusion. Photos of the final dies are shown in Figure 8 and dimensions are as specified in Table 1.

Table 1. Extruded and Sintered Dimensions of 10, 15, and 20% RD Square Cell LCA.

Relative Density	Cell Size (inch)	Cell Opening (inch)	Wall Thickness (inch)	Total Width (inch)	Bulk Density (g/cc)
10% As Extruded	0.260	0.247	0.013	1.313	
10% Sintered	0.196	0.186	0.010	0.991	0.82
15% As Extruded	0.260	0.240	0.020	1.320	
15% Sintered	0.196	0.181	0.015	0.997	1.23
20% As Extruded	0.260	0.233	0.027	1.327	
20% Sintered	0.196	0.176	0.020	1.002	1.64

(a) **(b)**

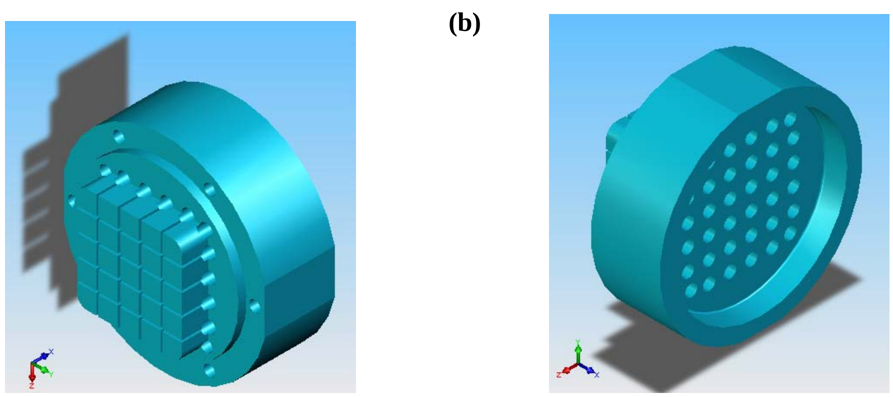

Figure 7. Square cell honeycomb extrusion die showing (a) die land and (b) paste feedholes.

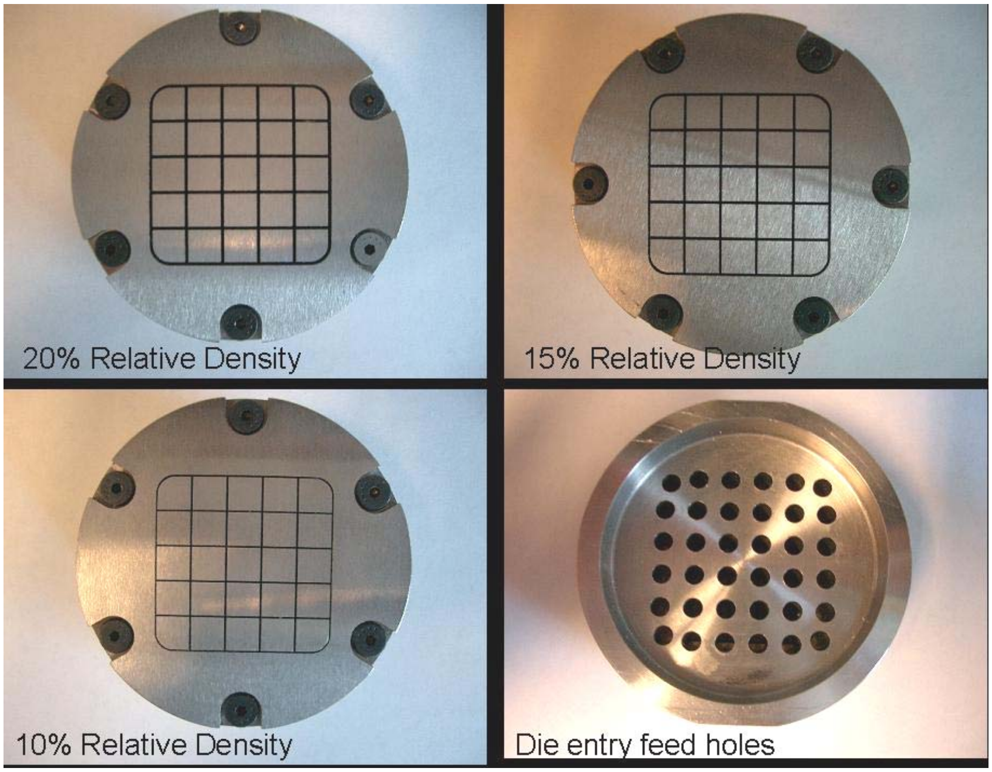

Figure 8. Photos of final square cell honeycomb extrusion dies with dimensions are as specified in Table 1.

Materials and Projected Properties - Alloys compositions for these extrusions were Super Invar and Maraging Steel 200 with compositions shown in Table 2. These compositions were compounded as particulate aqueous pastes at about 50% solids content. Iron was supplied with magnetite powder from Pea Ridge Iron Ore with a particle size of – 400 mesh. Nickel, cobalt, and molybdenum was supplied as metal powders with particle size of 1-8 micron all from AEE, Micron Metals. Titanium was supplied with titanium hydride with a particle size of 5-10 microns. Aluminum was not added. After extrusion, the honeycomb

Ultimate tensile strengths of the alloys made from LCA processing[3] are shown in Table 3. Super Invar in the as-reduced state is a ductile (25-30%) austenitic alloy. When cooled to Liquid N_2 temperature (78^{o}K), it converts to ~ 80% martensite and strength increases by 70% but ductility reduces to 8-10%. Maraging 200 from this process has been shown to have a strength of ~1200MPa with 3.5% ductility. When linear cellular structures are loaded axially in compression, they retain the same specific strength as the bulk material. Thus, the compressive strength, σ_c, of the square cell LCA were projected base on relative density as shown in Table 3. The ultimate results of the density variations and compositional changes will produce a wide range of compressive strengths, which should bracket the level of energy absorption desired by ARL, Aberdeen.

Table 2. Composition of Alloys.

Alloys	Composition (wt%)					
	Fe	Ni	Co	Mo	Ti	Al
Super Invar	62.9	31.8	5.4	NA	NA	NA
Maraging 200	69.9	18	8.5	3.3	0.2	0.1

Table 3. Estimate of Ultimate Tensile Strength of Alloys and Compressive Strength of LCA under axial loading at 10.15, and 20 % RD.

Alloys	UTS (95% RD) (MPa)	σc (10% RD) (MPa)	σc (15% RD) (MPa)	σc (20% RD) (MPa)
Super Invar (AR)	400	40	60	80
Super Invar (Liq N2)	680	68	102	136
Maraging 200	1220	122	183	244

AR - As-reduced, Liq N2 - Cooled to liquid nitrogen temperatures (78K)

Extrusion Results - As proposed, a minimum of six samples of each of the three compositions and three relative densities with a length of 5 inches was delivered. Also a similar set of six samples was delivered but with a length of 1 inch. To accomplish this, approximately twice as much honeycomb was extruded as need to supply the proposed deliverables. The extruded honeycomb was placed in open cell polyurethane foam supports after extrusion. The supports helped maintain straightness and provided uniform drying. The honeycomb was dried for a minimum of seven days at room temperature in humidity-controlled rooms. After drying, the best extrusions were cut to length in a table saw with a 10-inch carbide tipped blade. Extruded and dried samples were cut to lengths of one 1.3 and 7.0 inches to provide sample length of ~ 1.0 and 5.0 inches after reduction and sintering. The cut extrusions are shown in Figures 9-14. For most compositions and densities, approximately 50% more extrusion were cut and heat treated than proposed as can be seen in Figures 9-14. It can be seen in Figures 9-12, the extrusions for the 15 and 20% relative density samples were of reasonable quality both in cross section and straightness. However, for the 10% extrusions, Figures 13 and 14, considerable rippling of the sidewalls occurred on mostly one outside wall. This did reduce the quality of the extrusions but it was felt that testing with a 0.5 inch diameter projectile might be feasible so all the 10% were reduced and sintered.

All samples were in Figures 9-14 were reduced in a 50% hydrogen - 50% argon atmosphere at 1300^{o}C, Figures 15-16. The heating rate was approximately 1.0^{o}C /min to allow reduction and held at maximum temperature for 12 hours for sintering. Bulk density and dimensions for Super Invar (I) and Maraging 200 (M) steel LCAs after sintering are shown in Table 4. Densities and dimensions for the sintered samples were with in 5-10% of that proposed but unfortunately, considerable distortion occurred in the sintering process. The reason for the distortion is unknown at this time and this distortion has not been seen in smaller cell dimension LCA extrusions.

Table 4. Bulk density and dimensions for Super Invar (I) and Maraging 200 (M) steel LCMs after sintering.

LCM Type	I-20-1	I-20-2	I-15	I-10	M-20	M-15	M-10
Density (g/cc)	1.43	1.64	1.28	0.96	1.43	1.29	0.94
Density (g/cc)	1.46	1.68	1.31	0.97	1.44	1.26	0.91
Density (g/cc)	1.49	1.71	1.30	0.98	1.47	1.26	0.93
Density (g/cc)	1.54	1.66	1.25	0.99	1.44	1.23	0.95
Average (g/cc)	1.48	1.67	1.29	0.98	1.45	1.26	0.93
Std Dev	0.05	0.03	0.03	0.01	0.02	0.02	0.02
%Std Dev	3.2	1.8	2.1	1.3	1.2	1.9	1.8
Length (cm)	13.3	12.52	13.0	12.5	13.2	12.65	12.3
Width (cm)	2.5	2.35	2.4	2.2	2.45	2.35	2.2
Width (cm)	2.5	2.35	2.4	2.2	2.45	2.25	2.2

Deliverables – Samples of both Maraging Steel 200 and Super Invar were delivered to John Runyeon, Army Research Laboratory, Aberdeen Proving Ground, MD 21005-5066, runyeon@arl.army.mil.. Delivery was in January 2006. As noted, approximately 50% more samples with lengths of 5 inches were delivered than the proposed minimum of six samples of each of the three compositions and three relative densities. Also a similar set of six samples was delivered but with a length of 1 inch. At the request of ARL, Aberdeen, all the Super Invar samples were delivered in the as-reduced condition because conversion to martensitic invar only requires cooling in liquid nitrogen. This allowed maintaining maximum experimental flexibility.

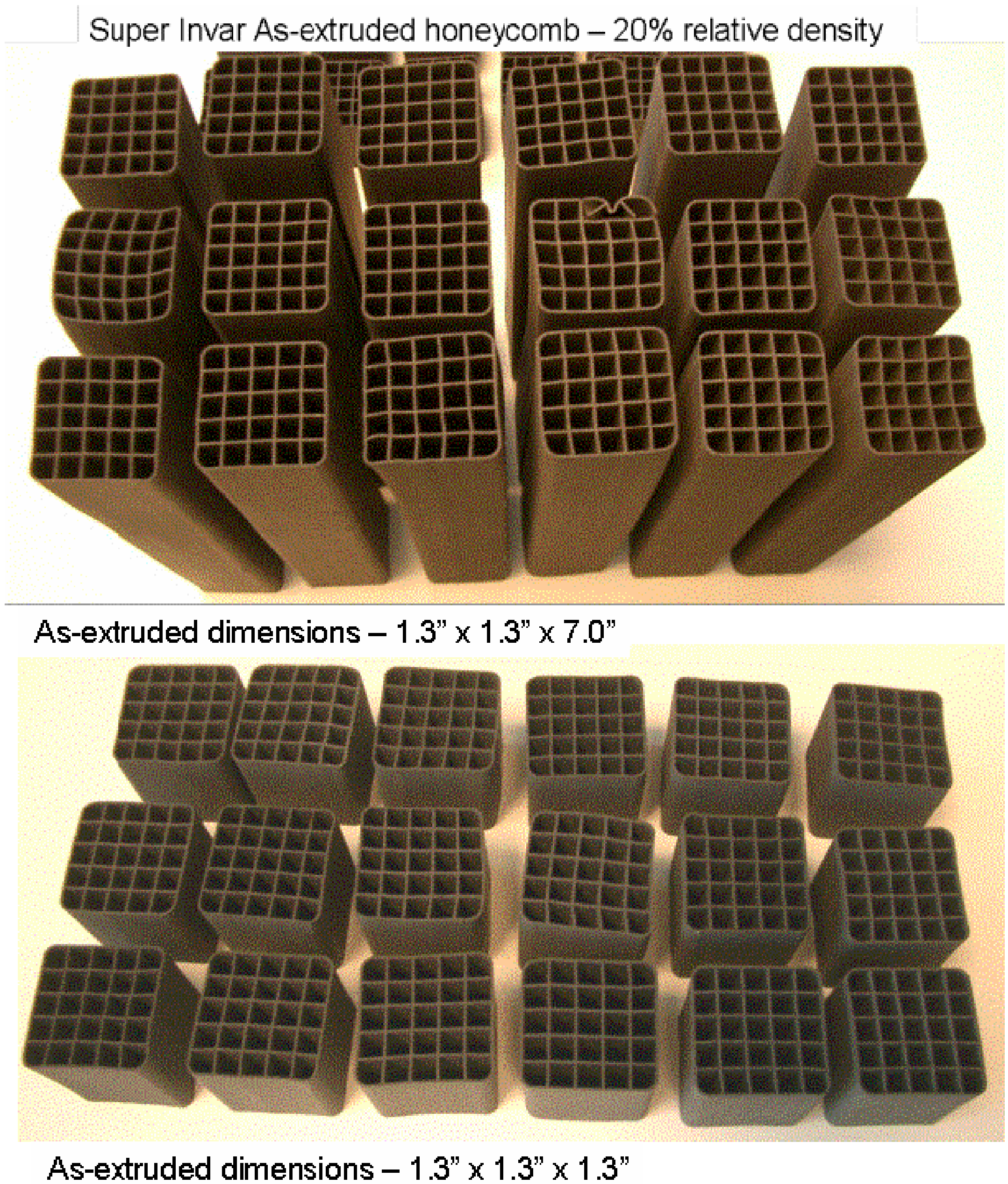

Figure 9. As-extruded Super Invar LCAs at 20% relative density. Dimensions are shown on photo.

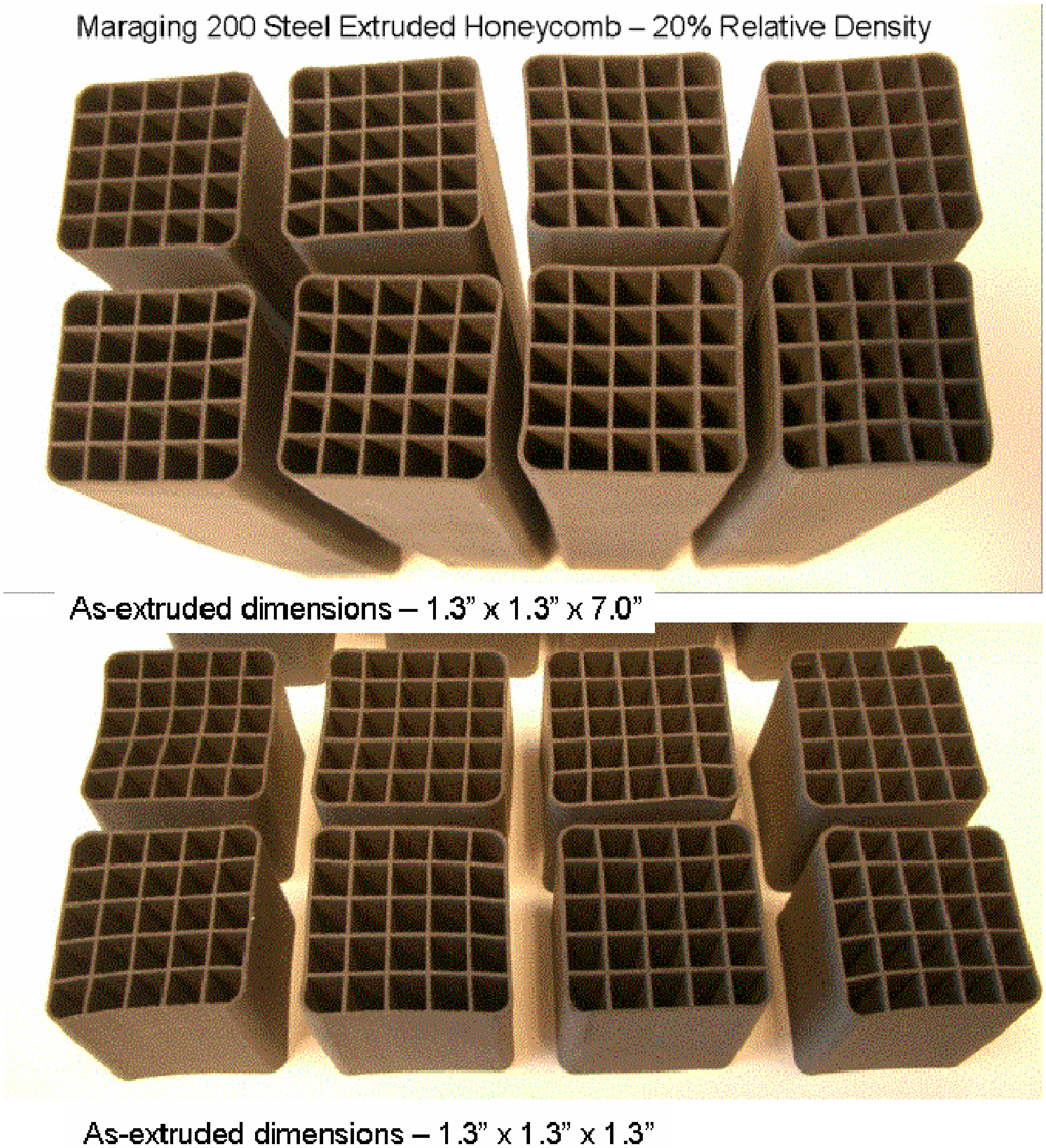

Figure 10. As-extruded Maraging 200 Steel LCAs at 20% relative density. Dimensions are shown on photo.

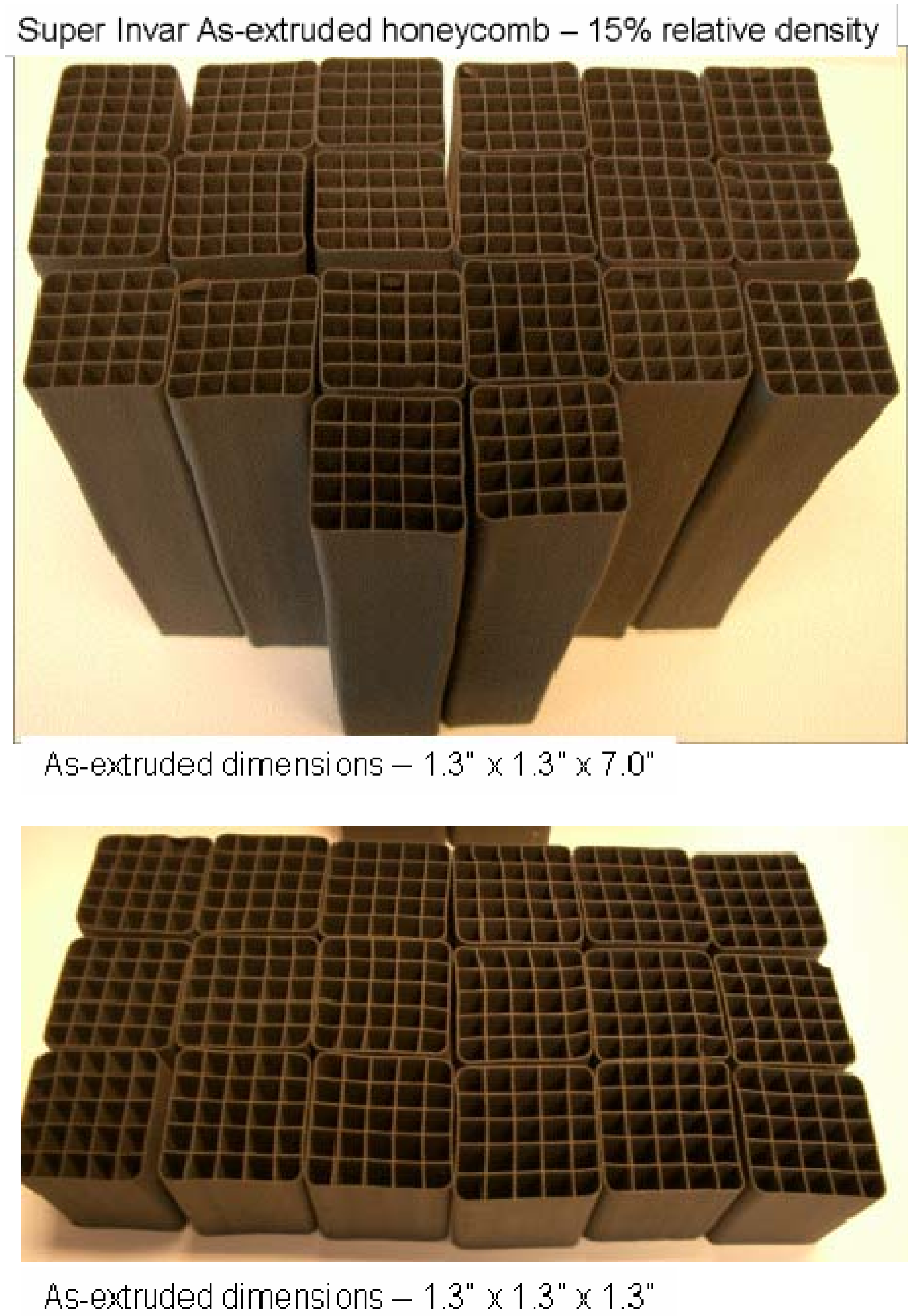

Figure 11. As-extruded Super Invar LCAs at 20% relative density. Dimensions are shown on photo.

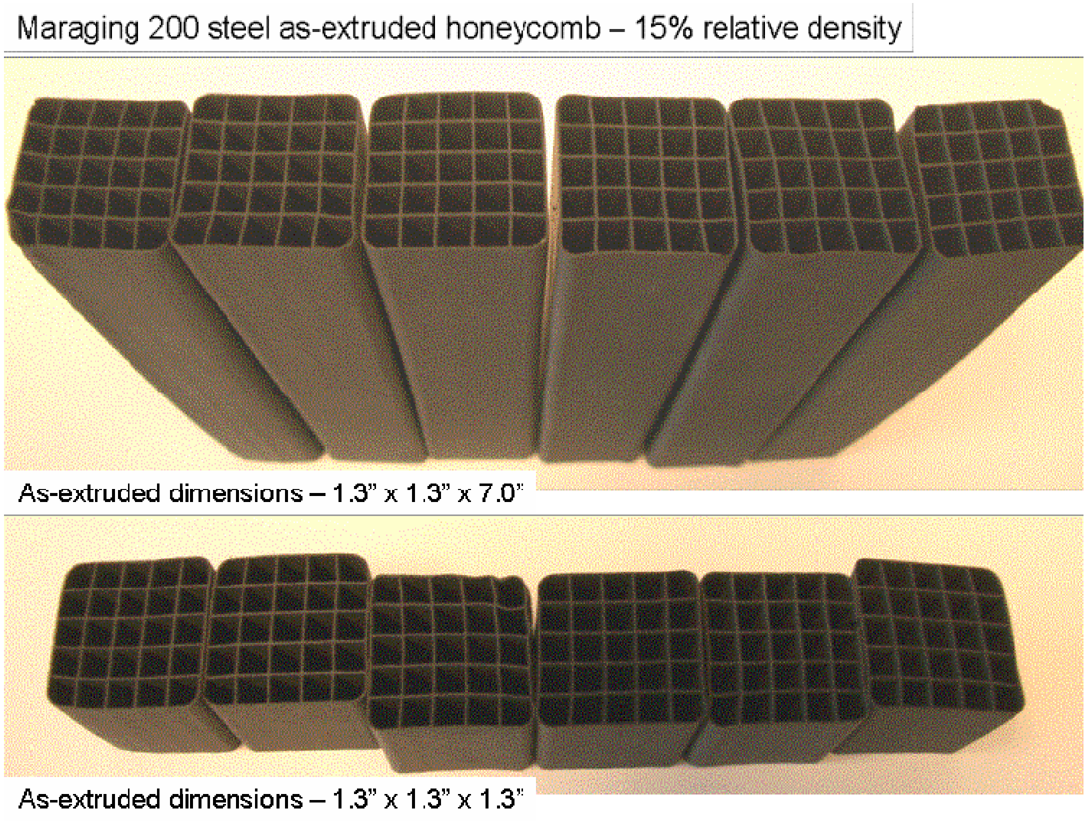

Figure 12. As-extruded Maraging 200 Steel LCAs at 20% relative density. Dimensions are shown on photo.

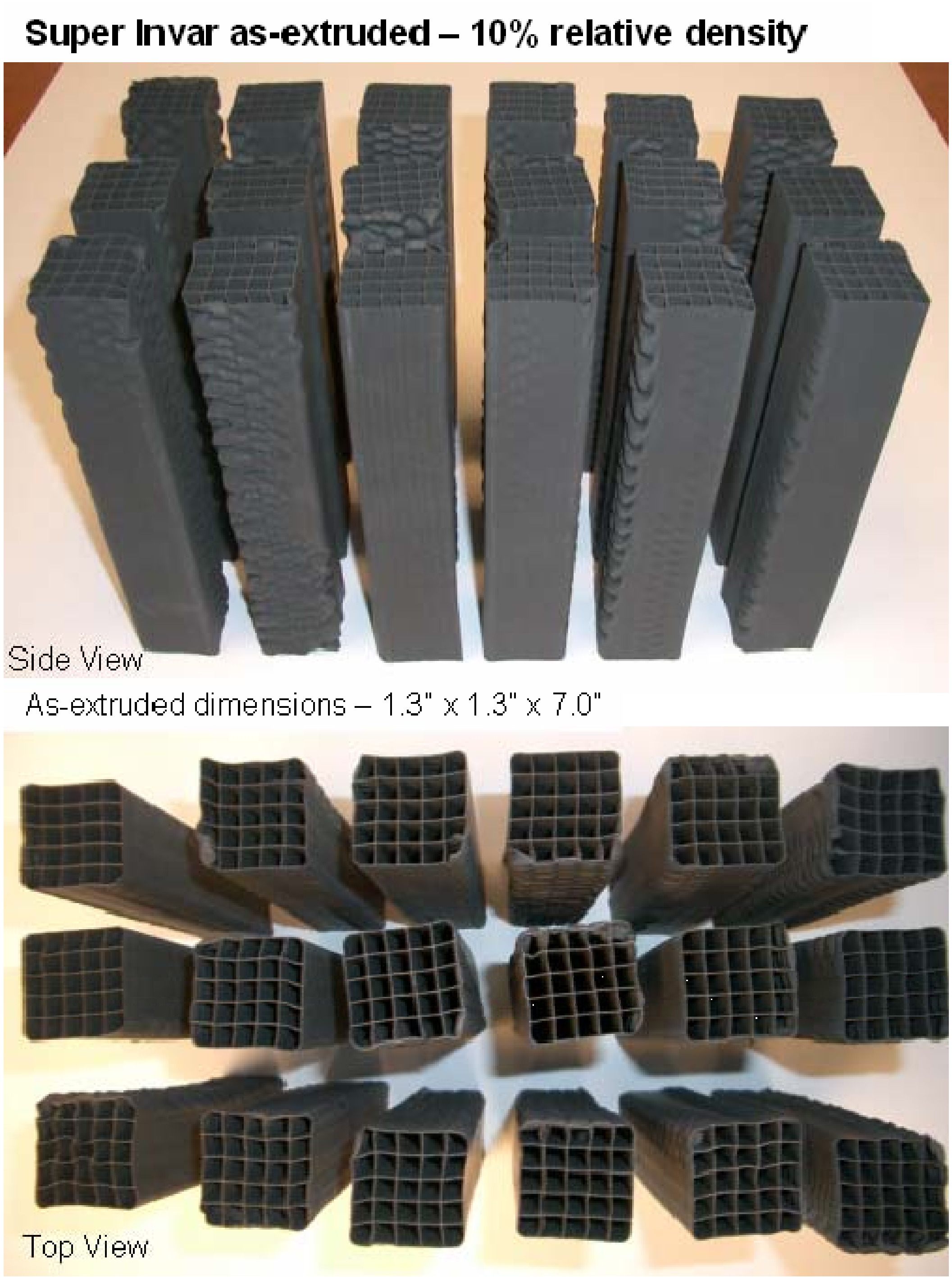

Figure 13. As-extruded Super Invar LCAs at 20% relative density. Dimensions are shown on photo.

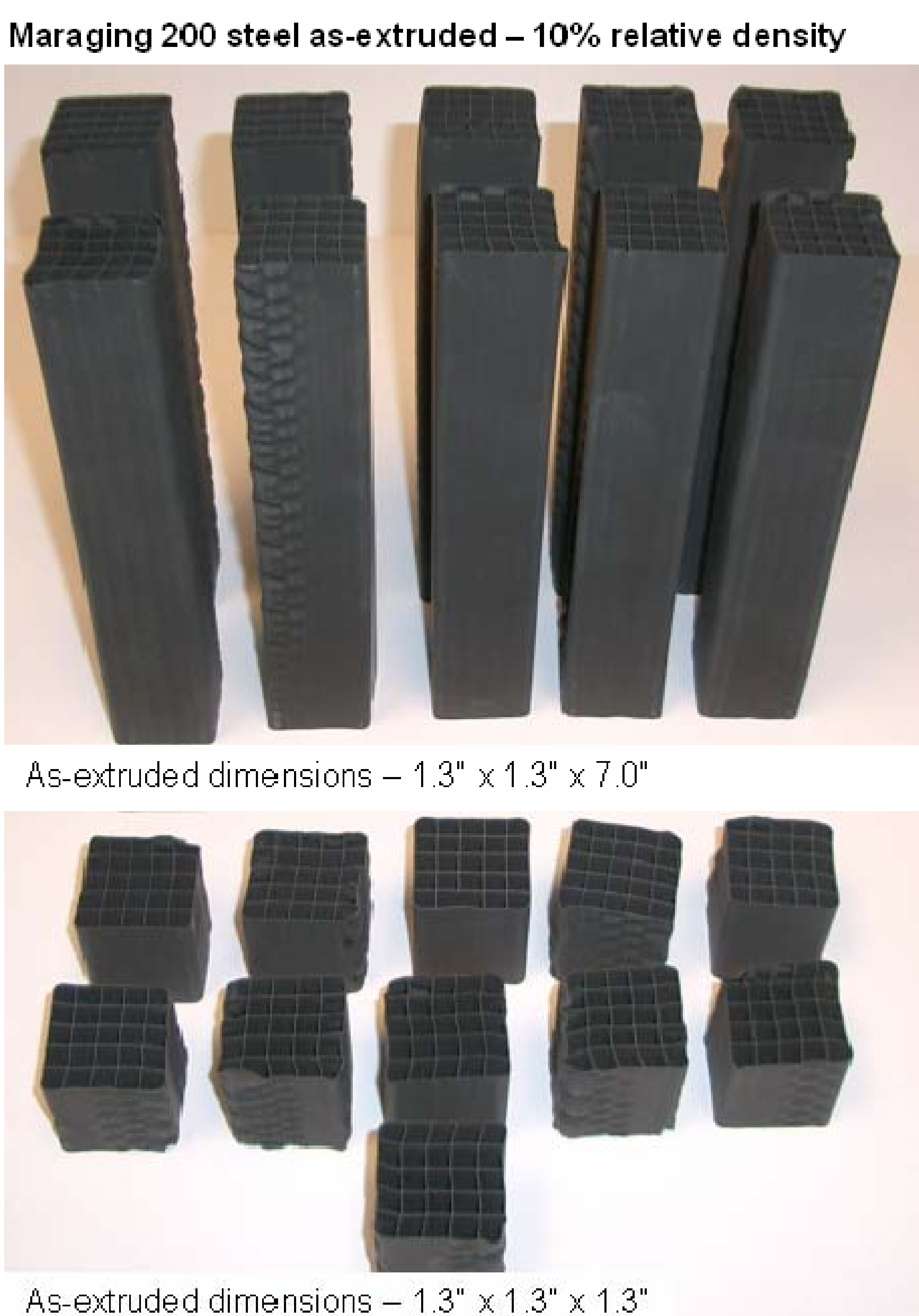

Figure 14. As-extruded Maraging 200 Steel LCAs at 20% relative density. Dimensions are shown on photo.

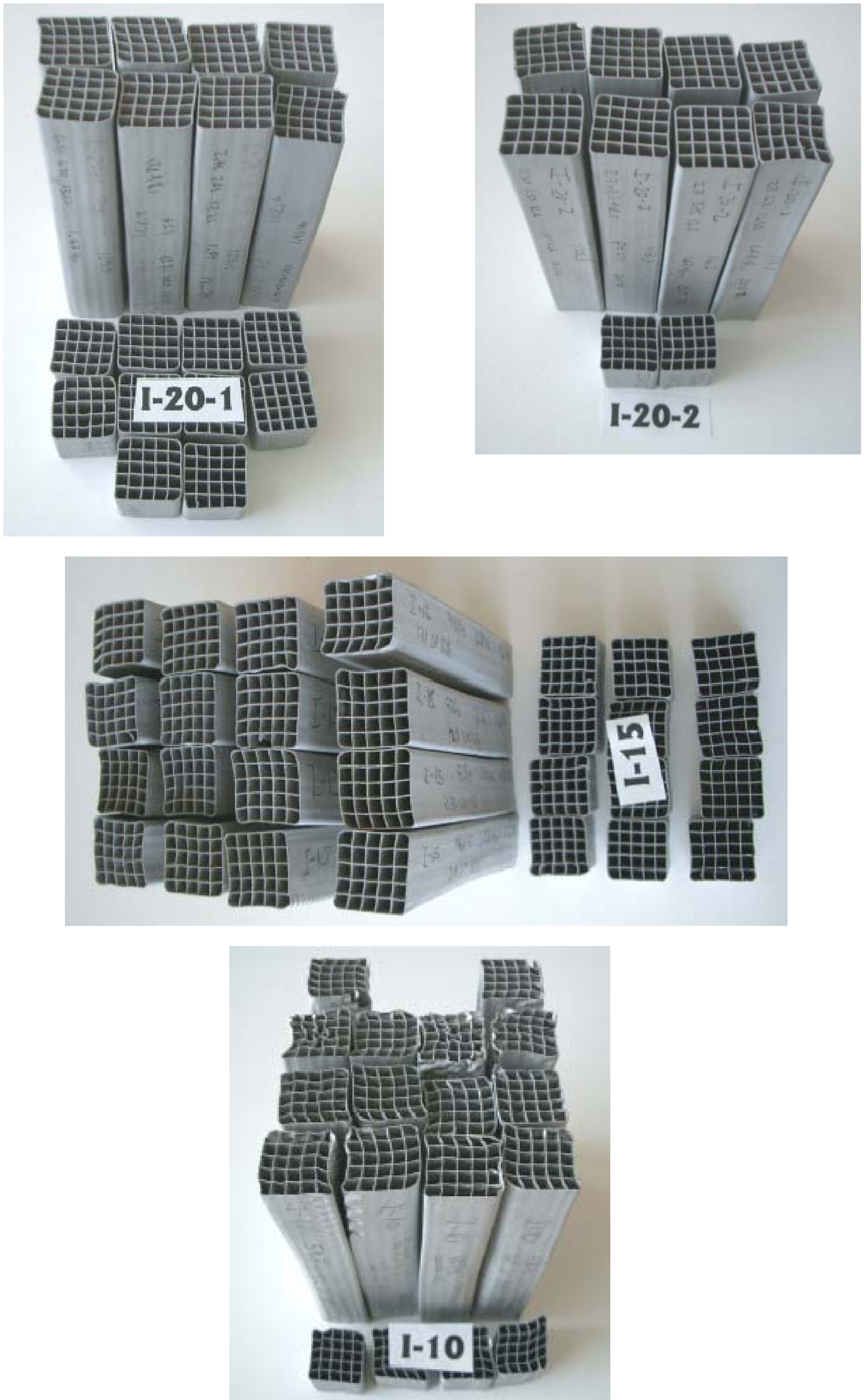

Figure 15. Final Super Invar LCAs delivered to ARL at 10, 15, and 20% relative density.

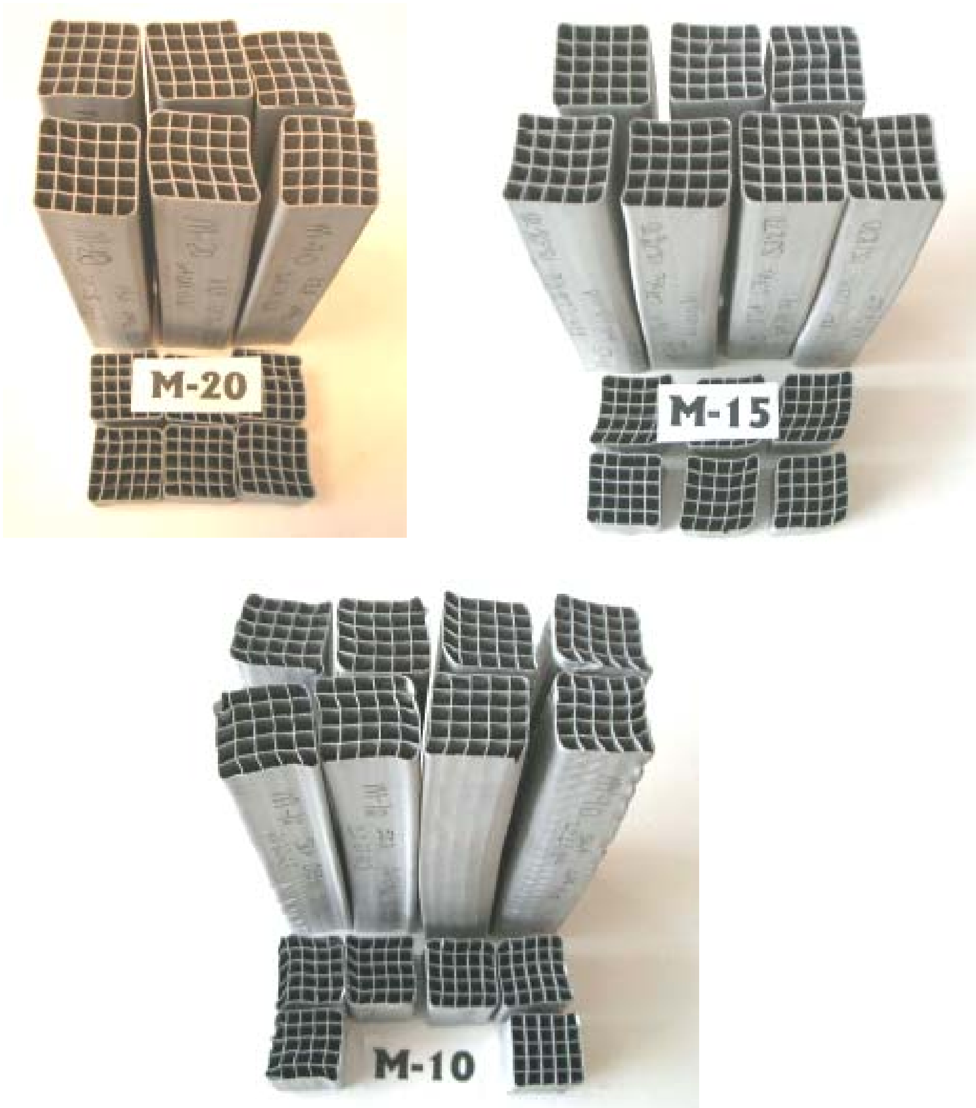

Figure 16. Final Maraging Steel LCAs delivered to ARL at 10, 15, and 20% relative density.